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Front Borerider Design Considerations for a Large-Caliber, Hypervelocity Kinetic Energy (KE) Projectile

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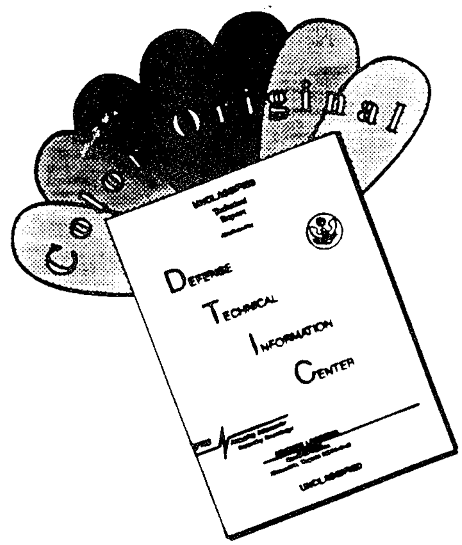

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There has been increased interest within the ballistic community to investigate the benefits of launching kinetic energy (KE) projectiles at hypervelocities, velocities in excess of 2 km/s. To facilitate such investigations, KE projectile designers have begun to employ 7-in cannons to achieve the higher desired velocities. Use of such large-bore guns results in increased aerodynamic loading on the front borerider scoop. Test firings of the AF4 7-in projectile resulted in catastrophic sabot failure upon muzzle exit. Based on these test data, a detailed investigation of the aerodynamic loads expected on a 7-in projectile launched at 2.4 km/s was undertaken as part of the Ballistics for Future Systems (BFUS) program. Three-dimensional finite element analysis techniques were used to determine the benefits of incorporating holes into the front borerider scoop. The benefits of utilizing splines were also examined. The result of this work is a design for a structurally robust, large-caliber, hypervelocity KE projectile.

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1. INTRODUCTION

In the early 1980s, the U.S. Army ballistic community adopted the double-ramp sabot as the most mass efficient means of launching long-rod kinetic energy (KE) projectiles. Design rules which sized the front and rear ramp tapers of the double-ramp configuration were developed (Drysdale 1981). A main bulkhead was placed between these two ramps over the projectile's center of gravity to enhance the in-bore stability of the round and support the obturator. The size of the bulkhead was determined by calculating the gas pressure load on the structure and then ensuring sufficient thickness to withstand the induced shearing force (Burns, Burton, and Drysdale 1992). The final component of the sabot structure was the front borerider, which serves a dual-purpose role. First, it is intended to help stabilize the projectile during in-bore travel to minimize the effects of transverse loading. Its second function is to provide a lifting surface to aid with the sabot petals' discard as the projectile exits the gun barrel. A sketch of a typical KE round, with its various parts labeled, is shown in Figure 1.

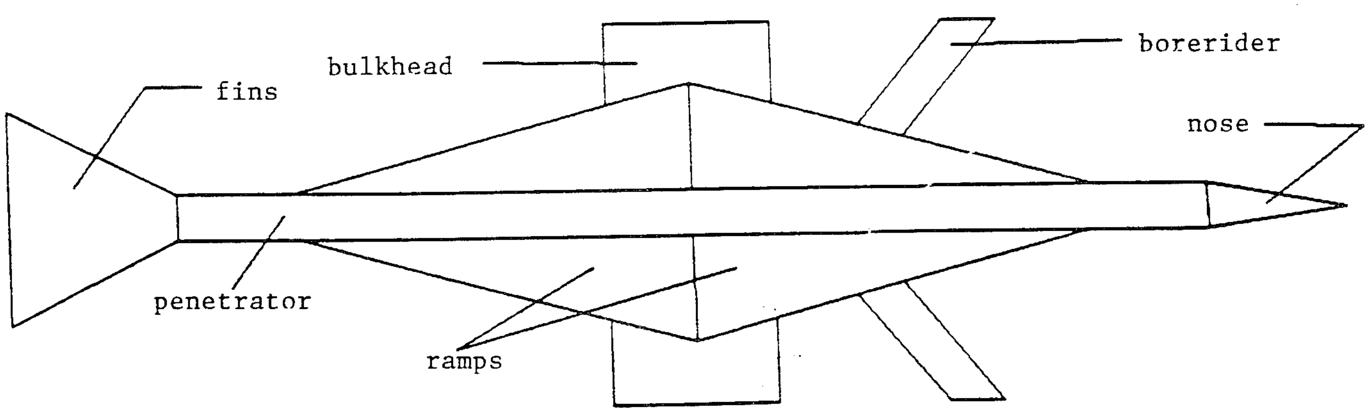

Figure 1. KE projectile components.

Development of design criteria for the front borerider has not evolved to the same extent as that for the sabot ramps or bulkhead. Typical design practice for a KE projectile dictates that a quasi-static finite element (FE) analysis be performed assuming the peak gas pressure load (Sorensen 1991). This ensures a robust projectile design capable of withstanding the in-bore axial pressure loads. These loads are minimal in the front borerider section of the projectile and play no role in its sizing.

One factor which does affect the structure of the forward borerider is the magnitude of the aerodynamic loads experienced at muzzle exit. Attempts have been made to develop analytical methods

to estimate these aerodynamic loads (Plostins 1985). The results of this work found that the technique developed overpredicted the critical stress level by as much as a factor of 2. Later on, 3-D FE techniques were used to investigate front scoop failures experienced in test firings of metal matrix sabots (Burns 1994). In general, however, the design of sabot forward boreriders made of an isotropic material, typically aluminum, for current tank cannon bore sizes (up to 120 mm) has been a trivial exercise.

The recent interest within the ballistic community to examine the benefits of hypervelocity (muzzle velocities above 2 km/s) has led to the use of larger bore guns to experimentally attain this velocity regime (Colburn, Ruth, and Robbins 1992). Test firings of KE projectiles, the AF4's, were conducted with a 7-in gun at Aberdeen Proving Ground, MD. A series of 10 shots was planned initially; however, during each of the first two shots, the front bell of the sabot was seen to have failed in the downrange smear camera photographs at velocities of approximately 2 km/s (Phillabaum 1994). It was speculated that these failures were caused by excessive aerodynamic loading on the frontal area of the forward scoop. At about this time, another 7-in KE projectile was being designed in an attempt to attain a launch velocity of 2.4 km/s for the in-house Ballistics of Future Systems (BFUS) program. Because of the failures experienced with the AF4 rounds, a detailed analysis and redesign of the front borerider of the BFUS projectile was undertaken to ascertain and minimize the effects of the aerodynamic loading. The details of this investigation are provided in this report.

2. INITIAL SABOT DESIGN

The initial sabot design for the 7-in BFUS projectile was done using Sorensen's FE optimization routine (Sorensen 1991). The projectile consists of a tungsten rod penetrator with a length-to-diameter ratio (L/D) of 30, supported by an aluminum sabot. The stress plot in Figure 2 shows the maximum stress values in both the penetrator and sabot (values are in pascals) are well below the respective material strengths given in Table 1. The quasi-static analysis technique employed to derive the Figure 2 stress plot uses a balance of peak gas pressure and acceleration to load the structure. Note that this method only minimally loads the front borerider and results in very low stress values through this section of the sabot. So while this analysis shows a projectile design capable of withstanding the in-bore acceleration and pressure loads, it does not address the aerodynamic loads encountered upon muzzle exit. Based on the AF4 sabot failures, it was deemed necessary to do a more detailed analysis of the front borerider to investigate the effects of the expected aerodynamic loads.

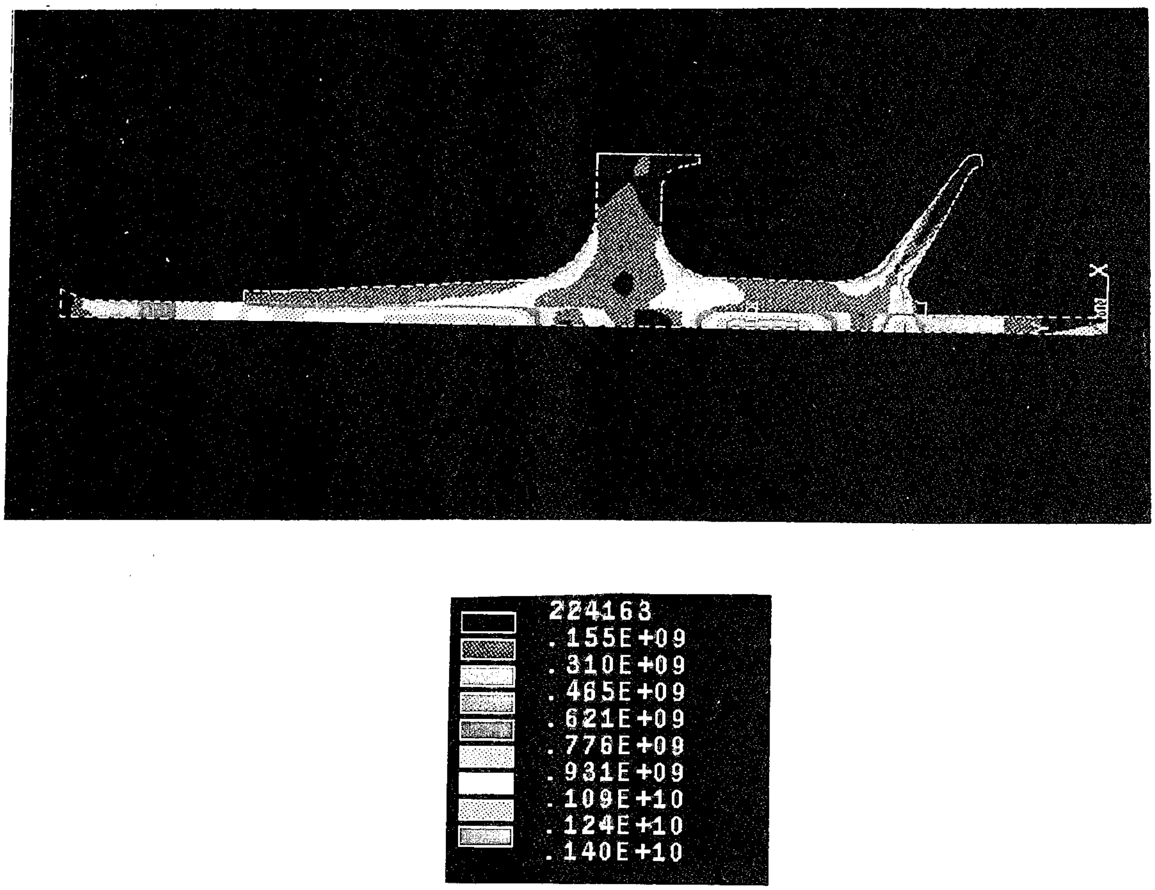

Figure 2. Stress plot of BFUS projectile.

Table 1. Material Properties Used in FE Analysis

Material	Density (kg/m^3)	Elastic Modulus (psi)	Compressive Yield Strength (MPa)	Tensile Yield Strength (MPa)
Tungsten	17,800	51,000,000	1,558	1,620
Aluminum	2,875	10,000,000	565	565

3. FORWARD SCOOP ANALYSIS

Using the premise that the AF4 sabot failures resulted from excessive aerodynamic loading on the front bell, a more detailed analysis of the BFUS projectile's forward scoop and saddle region was undertaken. (The saddle refers to the front ramp of the sabot located between the bulkhead and borerider.)

The most severe loading of the forward scoop under the aerodynamic pressure load occurs when the projectile begins to exit the gun tube. As the projectile transitions from in-bore to out-of-bore, the front borerider clears the muzzle while, for a short time, the obturator and supporting bulkhead are still in-bore. It is at this time that the front bell and saddle are most severely stressed since the forward scoop is fully loaded while the bulkhead and obturator are confined by the gun barrel. This situation is analogous to a cantilevered beam undergoing bending.

To represent this cantilever bending phenomena, it was not necessary to model the entire projectile geometry. Only a portion of the projectile was modeled (namely, the front borerider scoop and the saddle region) to examine the effects of the aerodynamic load on the front scoop of the sabot. A fixed boundary constraint was used at the rear of the finite element geometry model to simulate containment of the bulkhead and obturator by the gun tube, which thus inhibits discard of the sabot petals and induces bending.

Only one-half of a single 90-sabot petal was modeled to take advantage of symmetry and reduce the modeling and computation time of the exercise. A symmetry boundary condition was placed on one edge of the model. Figure 3 shows three views of the 3-D FE model of the 45° section (one-half of a sabot petal) used for the analysis.

First, Figure 3 gives an isometric view of the front bell and saddle from below the front of the sabot. In addition, a top view of the sabot is shown with the bottom edge being along a seam in the sabot. Finally, Figure 3 provides a side view of the same model representation shown in the previous views.

The load on the face of the frontal scoop was based on the stagnation pressure which develops behind a normal shock to the freestream static pressure. Equation 1 is taken from Plostins (1985) and is used to calculate the stagnation pressure, P_s.

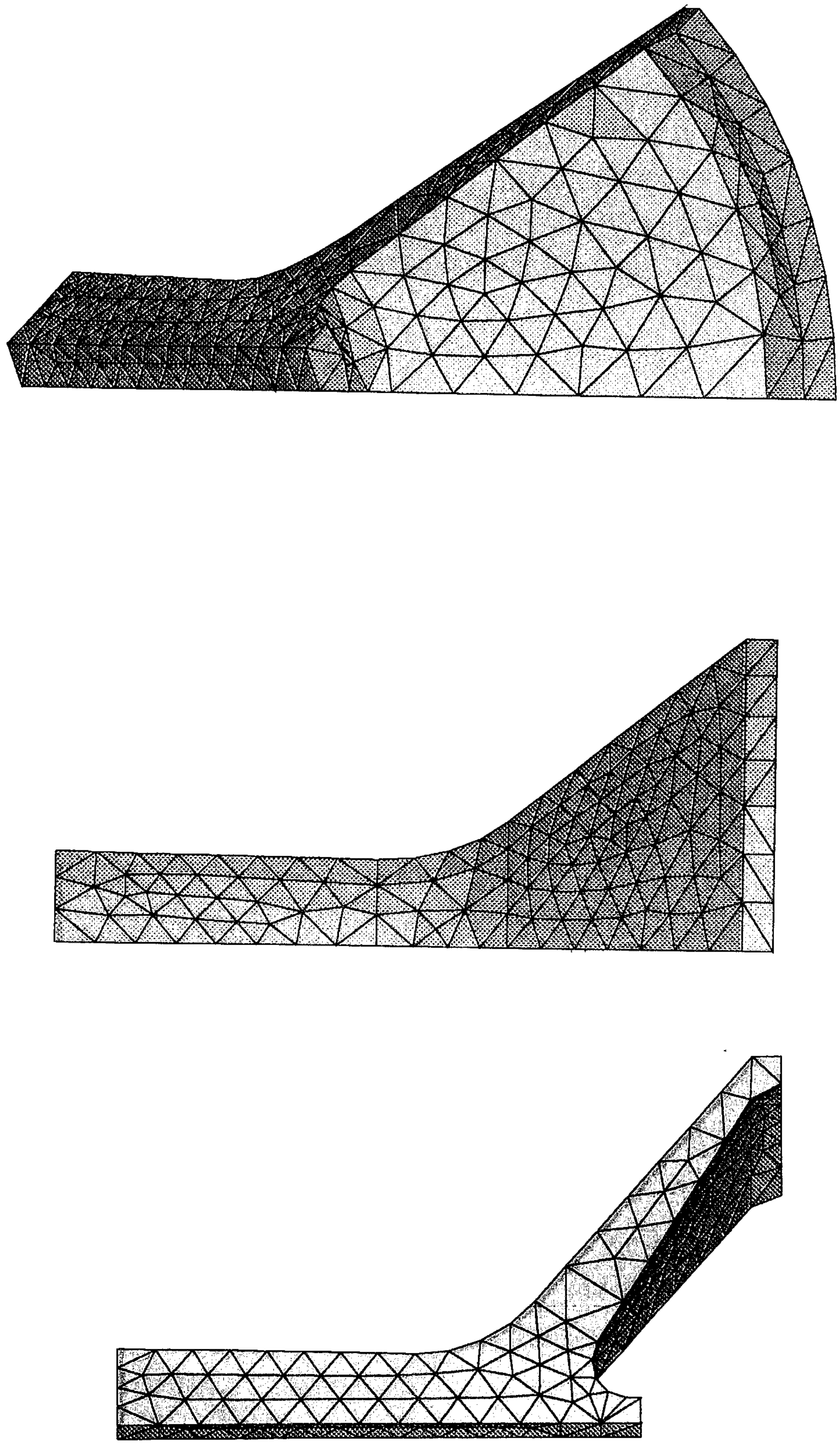

Figure 3. 3-D FE model of 45° section of front borerider and saddle region.

$$|P_s| = P_\infty \left(\frac{6M_\infty^2}{5} \right)^{\frac{7}{2}} \left(\frac{6}{7M_\infty^2 - 1} \right)^{\frac{5}{2}} , \quad (1)$$

where M_∞ is the mach number and P_∞ is the freestream static pressure. P_∞ was assumed to be 14.7 psi (101.4 MPa), while the mach number was calculated using

$$M_\infty = \frac{V_{muz}}{V_{sound}} , \quad (2)$$

where V_{muz} is the expected muzzle velocity and V_{sound} is the speed of sound and is given by

$$V_{sound} = 49.1\sqrt{T} ,$$

where T is the temperature in degree rankine and yields V_{sound} in feet/second. Assuming ambient temperature conditions (T = 530 R), equation 3 yields V_{sound} equal to 1,130.4 ft/s (344.5 m/s). Dividing this value into the desired muzzle velocity of 2.4 km/s produces a mach number of 6.966, per equation 2. Substitution of this mach number into equation 1 results in a pressure load of 925 psi (6.38 MPa) on the front scoop which was incorporated into the FE model.

4. BORERIDER DESIGN ITERATIONS

The initial baseline case was for a full, frontal borerider scoop loaded with 925-psi pressure. A plot of the resulting effective Von Mises' stress through the structure for an elastic analysis is shown in Figure 4. The stress contour values on the plot are given in pascals. The front borerider and saddle region are made of aluminum, which from Table 1 has a yield strength of 565 MPa. Thus, from the color contour plot, it is seen that the entire saddle region experiences stresses exceeding its load carrying capability. These high stress values result from the loading in the large scoop acting to cantilever the

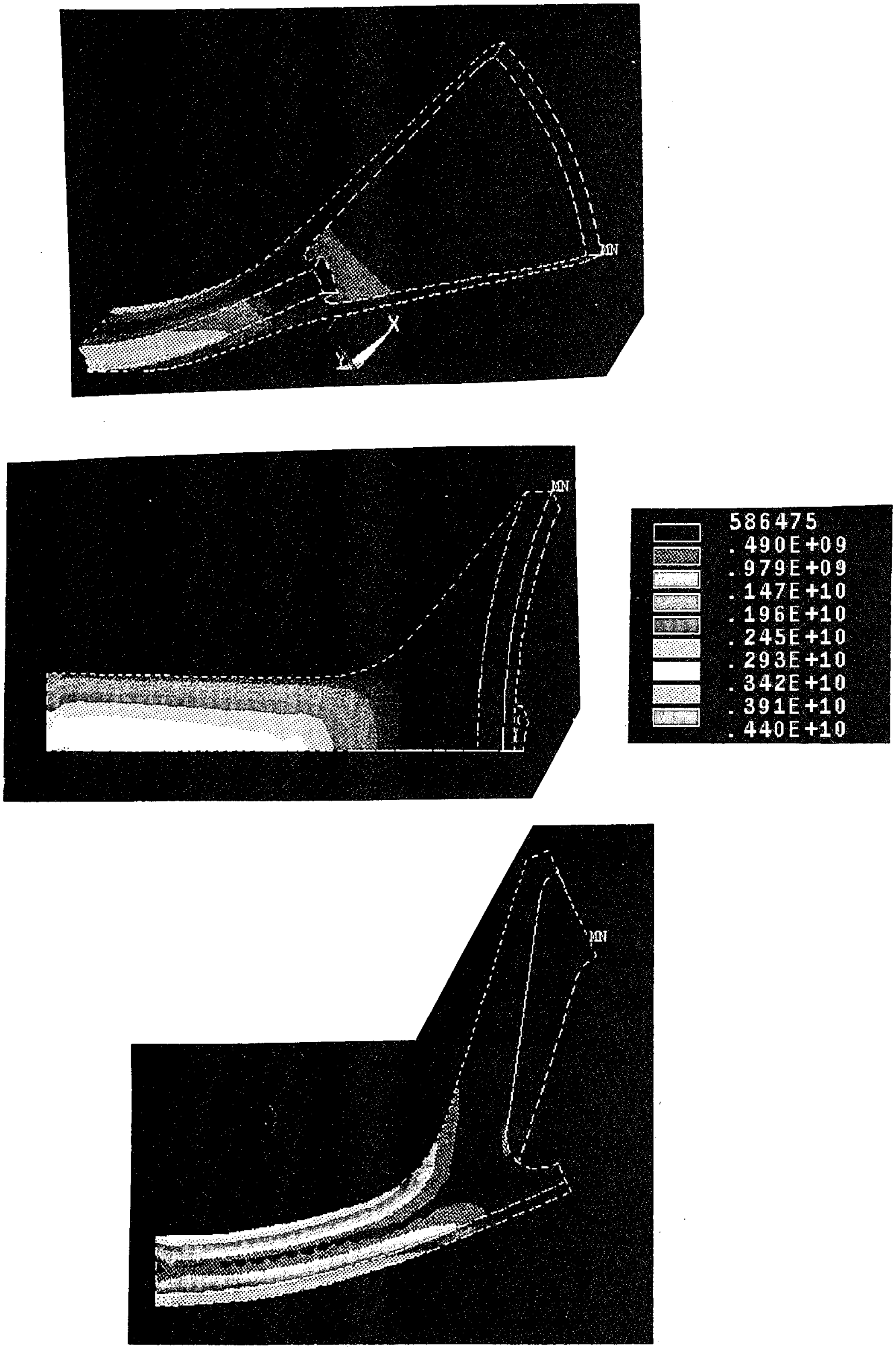

Figure 4. <u>Case 1 stress plot - full frontal scoop</u>.

entire section about the pinned aft end. This situation is analogous to the condition that occurs at muzzle exit when the front of the projectile (front borerider) has cleared the barrel end while the bulkhead and obturator remain inside the launch tube. This is also consistent with the sabot failures experienced during the test firings of the AF4 projectile.

The first modification made to alleviate the stress state was to put a circular hole through the borerider scoop to reduce the frontal area loaded by the aerodynamic pressure. This initial hole size was selected to reduce the frontal area by 33%. Figure 5 shows the resulting stress plot with a 48.26-mm-diameter hole through the scoop. While a reduction in stress is achieved, it is not sufficient to prevent failure in the saddle. Also note that a high stress area can be seen at the base of the borerider due to the reduced thickness in this region.

The next iteration, case 3, maximized the hole size through the borerider. Here, a 58-mm-diameter hole was modeled with the stress plot shown in Figure 6. At this point, it is seen that the predominant high stress region is localized at the base of the borerider, while stresses in the saddle region still exceed the yield strength of the aluminum.

The case 3 analysis, showing the maximum allowable circular hole size to be insufficient in alleviating the high stress state, led to use of a window-shaped cutout being incorporated into the case 4 analysis. The window size was selected to be equal to the area of the 48.26-mm hole used in case 2, thus again reducing the frontal area by 33%. The stress plot results of case 4 are provided in Figure 7, and as with the previous case, there is a high localized stress region at the narrow base of the borerider support.

After examining the case 4 borerider design, it was felt that much of the material away from the borerider base could be removed without adversely affecting the strength of the structure. This led to a 60° window being incorporated into the front borerider for case 5 (30° in the 45° sabot petal model). Figure 8 shows the stresses which result from this modification, and while they are reduced, there is still a high stress region at the borerider base.

Case 6, shown in Figure 9, maintained the 60° window configuration but thickened the borerider base by adding material to the bottom of the cutout window. This design, while exhibiting a high localized stress region, shows significant portions of the saddle and borerider to be within the yield limits of the aluminum. These results led to one final modification of the window shape.

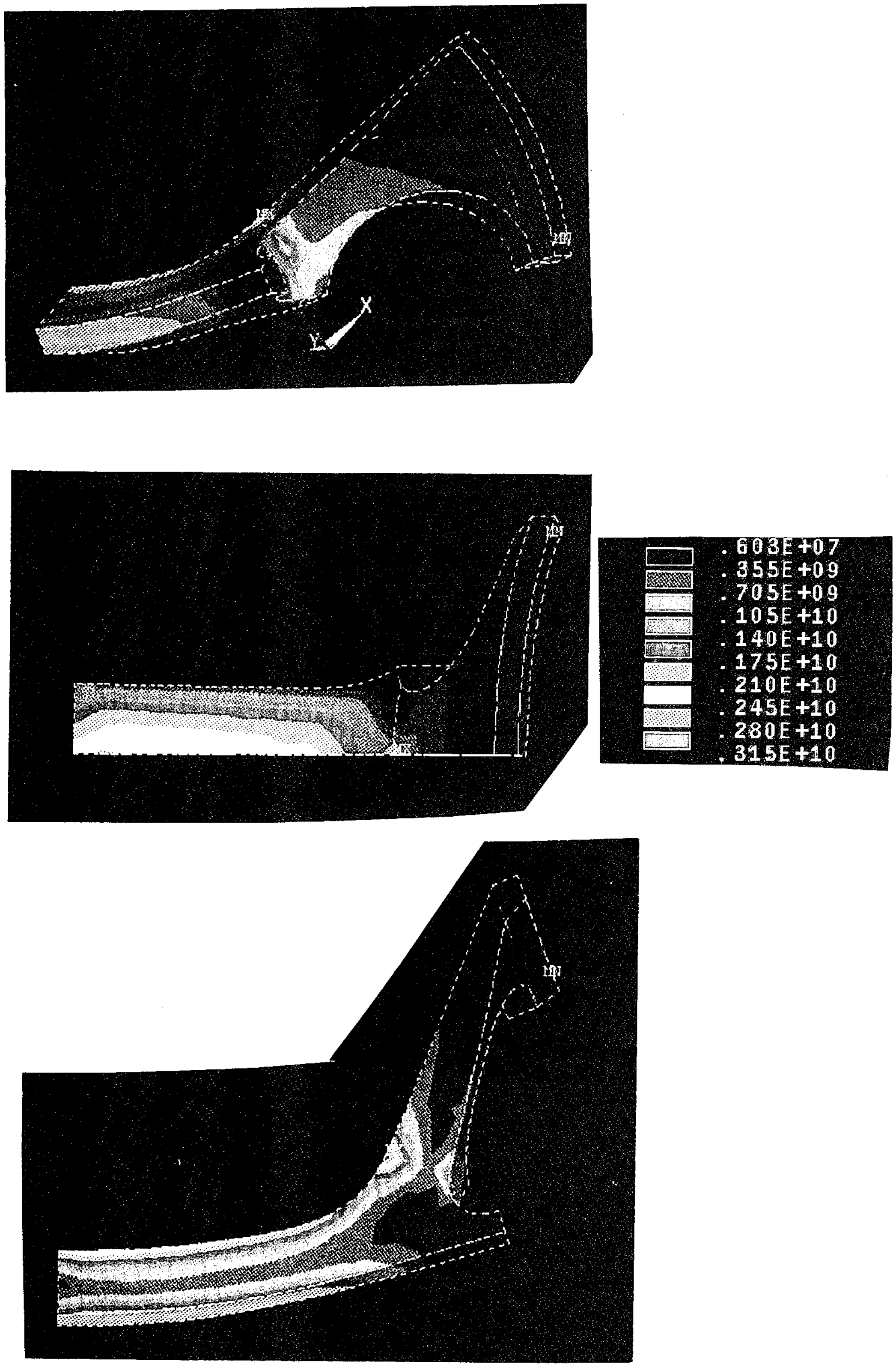

Figure 5. Case 2 stress plot - 48.26-mm circular hole.

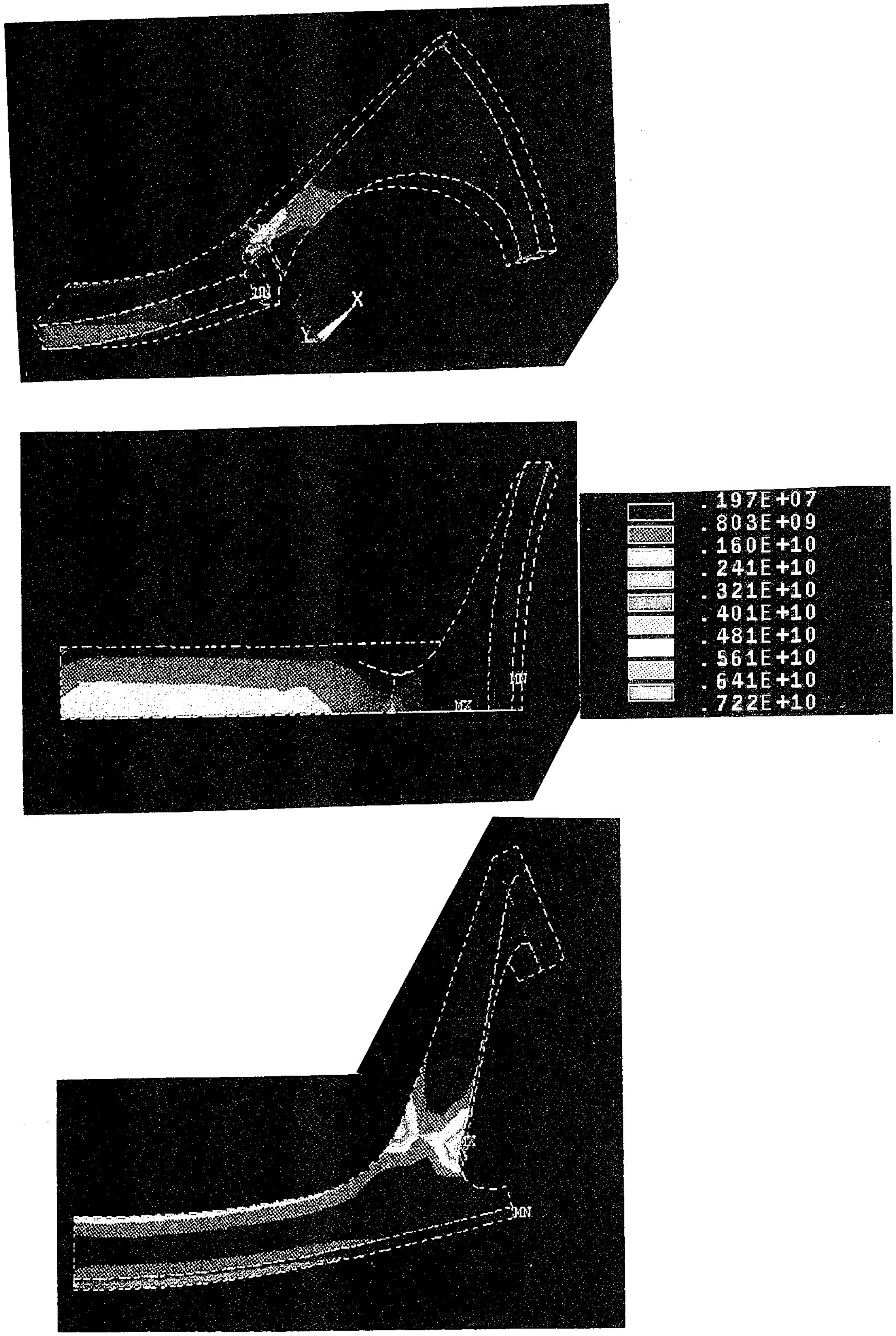

Figure 6. Case 3 stress plot - 58-mm circular hole.

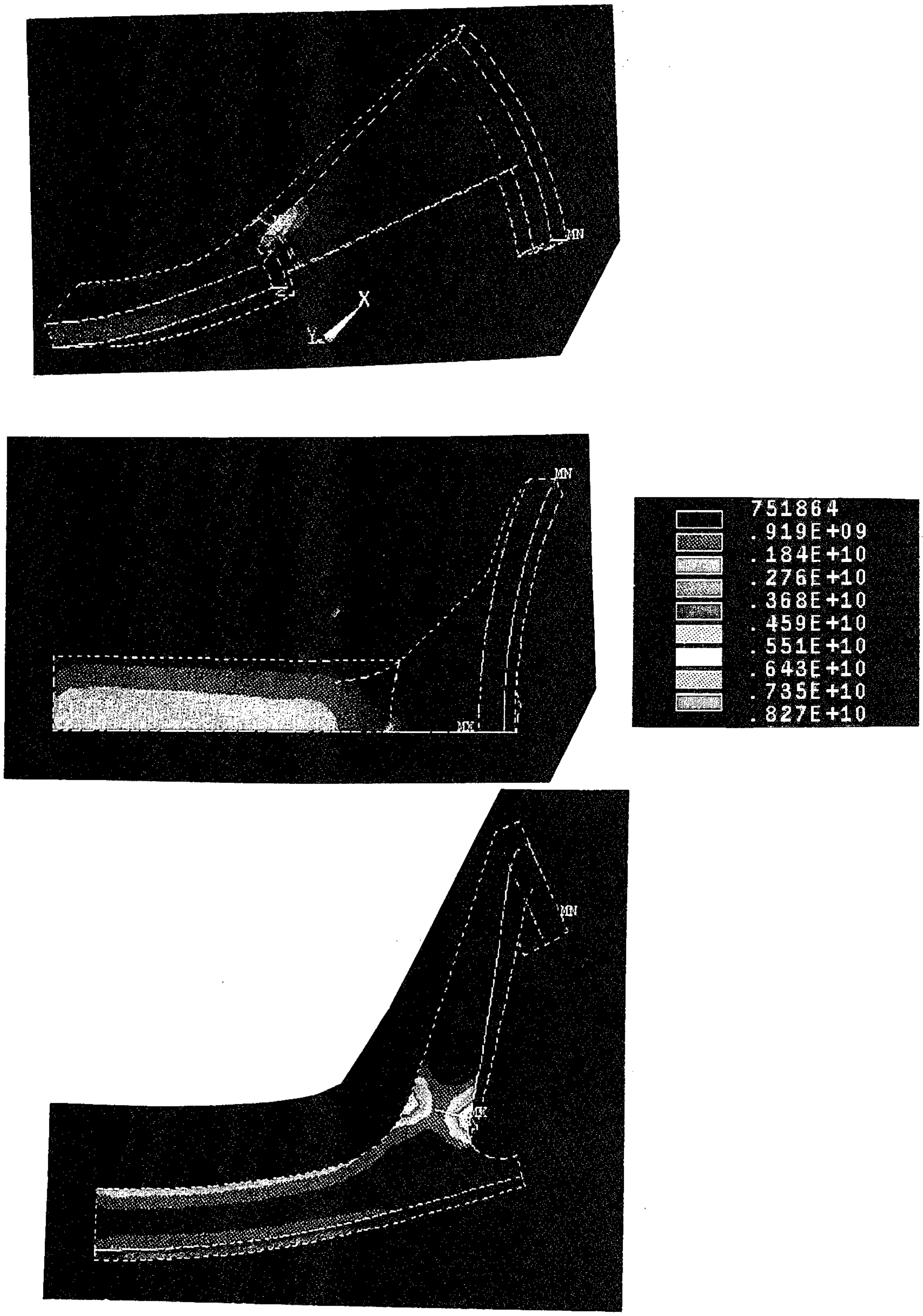

Figure 7. Case 4 stress plot - 32° window.

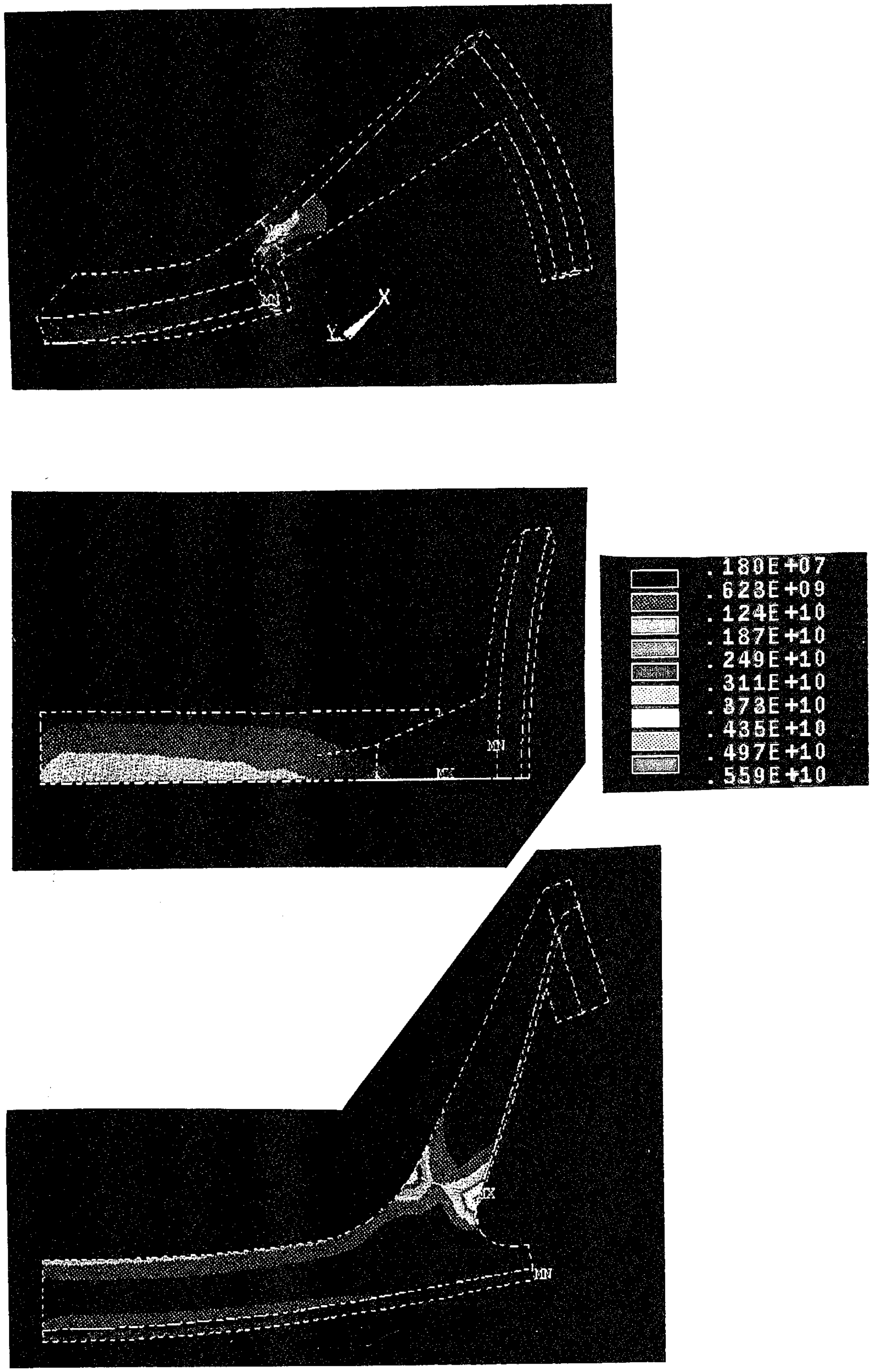

Figure 8. Case 5 stress plot - 60° window.

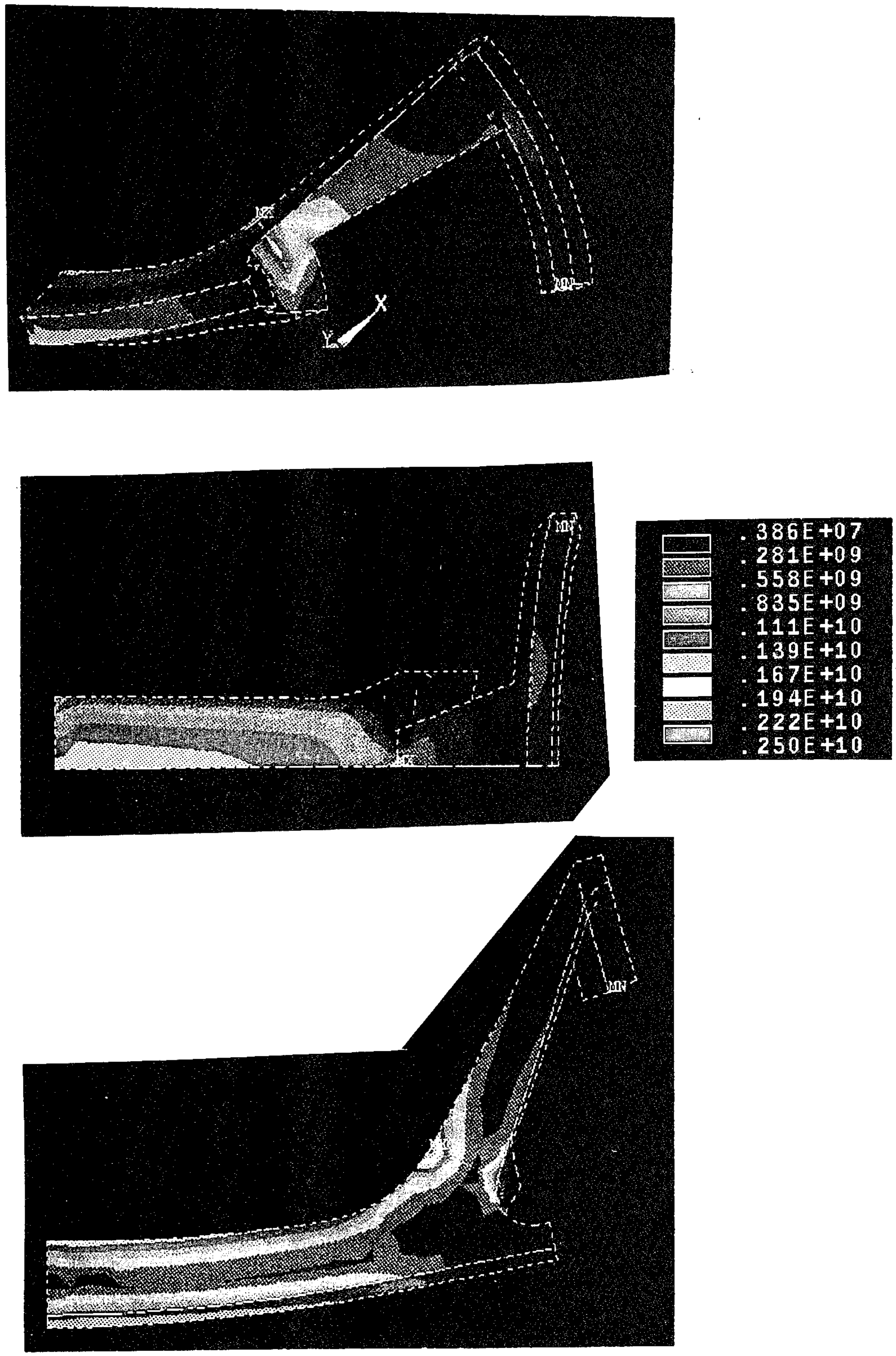

Figure 9. Case 6 stress plot - smaller 60° window.

The new modified window, seen in Figure 10, further opened up the top of the window, resulting in a uniform thickness radial support. This "spoked-wheel" arrangement, case 7, shows dramatic improvement in the region's stress state. The high localized stresses are reduced by 25%, while much of the through sections are below the yield criteria.

At this point in the analysis, it was felt that the material removed from the borerider scoop had been maximized and further modifications to the window configuration were impractical. Table 2 is provided to summarize the changes made in going from the full front scoop, case 1, to the spoked-wheel configuration of case 7. The region of high stress is listed for each case, in addition to the mass of the structure (total borerider and saddle mass) normalized against the case 1 value. Thus, from Table 2, the design of case 7 has a mass 36.3% less than the full scoop design.

Having run the gamut of modifications to the borerider window, it was time to examine the benefits of adding material back into the structure to strengthen it. The initial 2-D quasi-static design of the projectile (Figure 2) produced a predicted launch package mass of 17.8 lb (8.07 kg). Interior ballistic code runs estimated that a projectile of this mass could attain a 2.4 km/s launch velocity from a double-travel 7-in gun (Colburn 1994). Since attaining this velocity level was a principal goal of the BFUS projectiles, any additions to the saddle and borerider would have to keep the normalized mass below the baseline, case 1 value.

In this vein, the radial borerider, or "spoke," was thickened. The stress plots of this case 8 analysis are shown in Figure 11. The borerider spoke exhibits all through-section stress values below that of yield. The problem has now been isolated to the saddle region. It is ironic that we have now returned to the situation found in case 1—that is, acceptable borerider stress levels but excessive values in the saddle region. However, by comparing Figure 11 to Figure 4, we see that the maximum stress in the saddle has been reduced 68% while also achieving an 18% reduction in structure mass.

As was described previously for the case 1 results, the high saddle stresses result from the bending induced by the loading on the surface of the front scoop. Work done in other projectile design programs (Kaste and Wilkerson 1992) has shown that by incorporating splines or ribs into the sabot, one can greatly reduce the bending stress in the sabot. Thus, such an approach was adopted for case 9, which added a small spline to the saddle, aft of the borerider support. The resulting stress plot in Figure 12 shows that

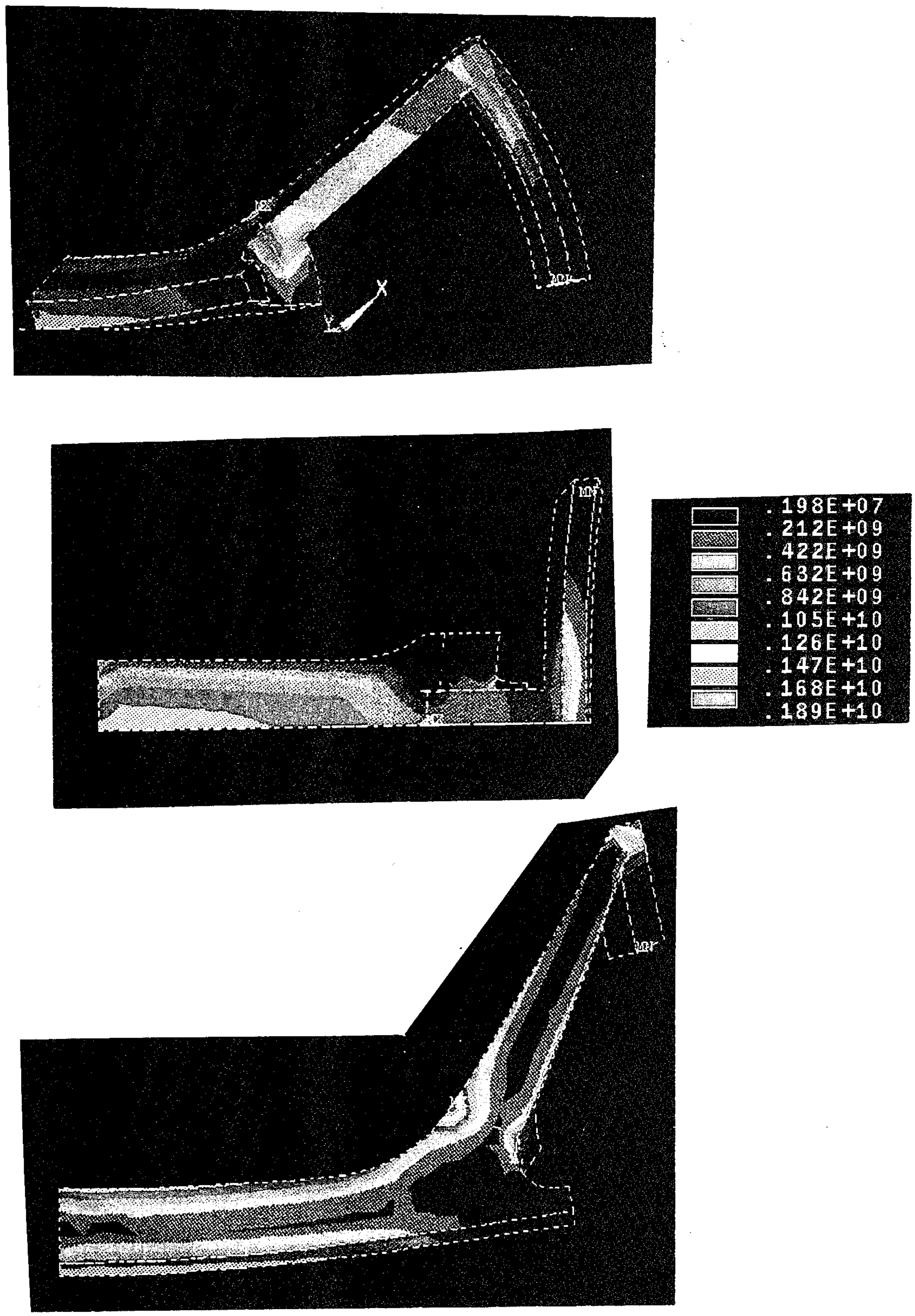

Figure 10. Case 7 stress plot - spoked-wheel arrangement.

Table 2. Summary of FE Design Iterations

No.	Sabot/Front Borerider Geometry Description	High Stress Region	Normalized Mass
1	Full front borerider scoop	Saddle	1.0
2	48.26-mm-diameter holes (1/3 frontal area)	Saddle	0.803
3	58-mm-diameter holes	Base of borerider	0.698
4	32° window in 1/4 section (16° in model)	Base of borerider	0.803
5	60° window in 1/4 section (30° in model)	Base of borerider	0.637
6	Smaller 60° window in 1/4 section	Saddle/base of borerider	0.690
7	Modified 60° window - spoked-wheel configuration	Saddle/base of borerider	0.637
8	Modified 60° window, reinforced borerider thickness	Saddle	0.820
9	Modified 60° window, reinforced borerider thickness, small spline	Saddle	0.862
10	Modified 60° window, reinforced borerider thickness, large spline	Saddle and spline	0.898
11	Modified 60° window, reinforced borerider thickness, quadrilateral spline	Localized at spline base	0.965
12	Modified 60° window, reinforced borerider thickness, quadrilateral spline (elastic-plastic analysis)	Localized stress concentration	0.965

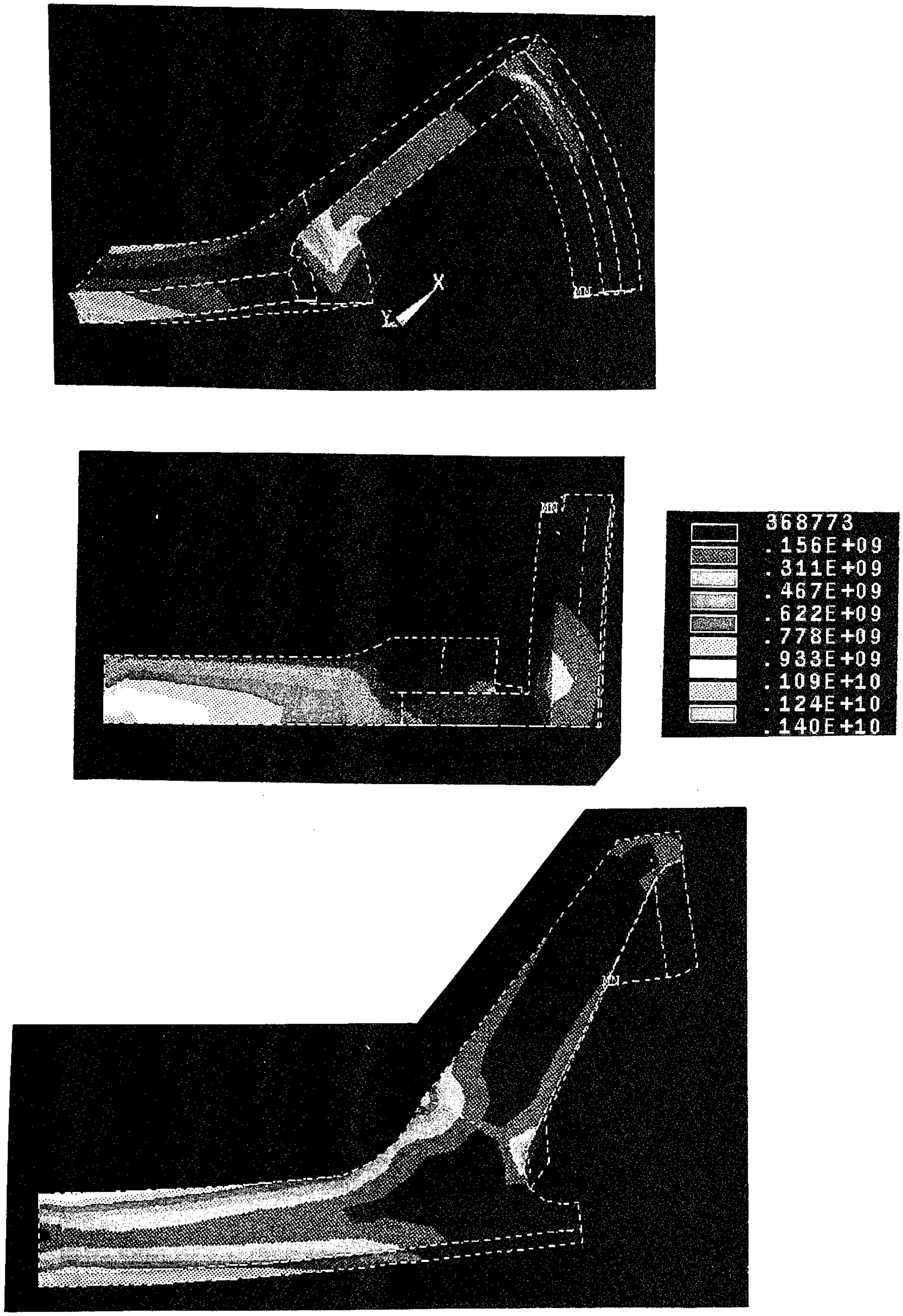

Figure 11. Case 8 stress plot - reinforced borerider thickness.

all stress values in the borerider are well below the 565-MPa yield strength of aluminum. While there are no through-section stress values exceeding yield, there still exist substantial areas of the saddle which do.

The next iteration, case 10, used a longer spline which nearly extended to the end of the saddle region. Figure 13 shows that while the regions of high stress have been made smaller, they are still quite substantial. This led to a final modification, case 11, which used a quadrilateral, as opposed to triangular, spline configuration. This enlarged spline reduced all stress values below the yield criteria except for localized concentrations at the corner of the spline where it interfaces with the saddle (see Figure 14). As listed in Table 2, the mass of this geometry was 96.5% that of the baseline design, meaning further additions to the spline could not be made without exceeding the established mass criteria.

The final iteration, case 12, was made and examined the quadrilateral spline configuration with an elastic-plastic analysis. By incorporating plasticity into the model, the high stress concentration areas such as the notch at the base of the spline could be alleviated. Figure 15 gives the results of the elastic-plastic analysis. Nearly all of the structure is within the yield limits of the material. The few regions not below yield are highly localized and will likely be reduced further when the spline is actually configured as a blend into the saddle, as opposed to a notch. Figure 16 shows a schematic of the finalized sabot design.

5. CONCLUSIONS

The desire of KE projectile designers to investigate the benefits of higher launch velocities has led to the use of larger and more powerful cannons. In particular, 7-in guns have been used to test full-scale penetrators at velocities well above current ordnance. The combination of larger sabots and higher velocities requires that greater attention be paid to the details of the front borerider and saddle region design.

This report has provided a step-by-step design approach to minimize the effects of aerodynamic loads on the KE projectile structure. The 3-D FE analysis shows the benefits of reapportioning mass from the front scoop to a thicker borerider support and an abutting spline. The affect of the design iterations was to take a full front borerider scoop which was predicted to catastrophically fail and modify it into a robust configuration. These modifications were accomplished with no additional parasitic mass to the baseline configuration.

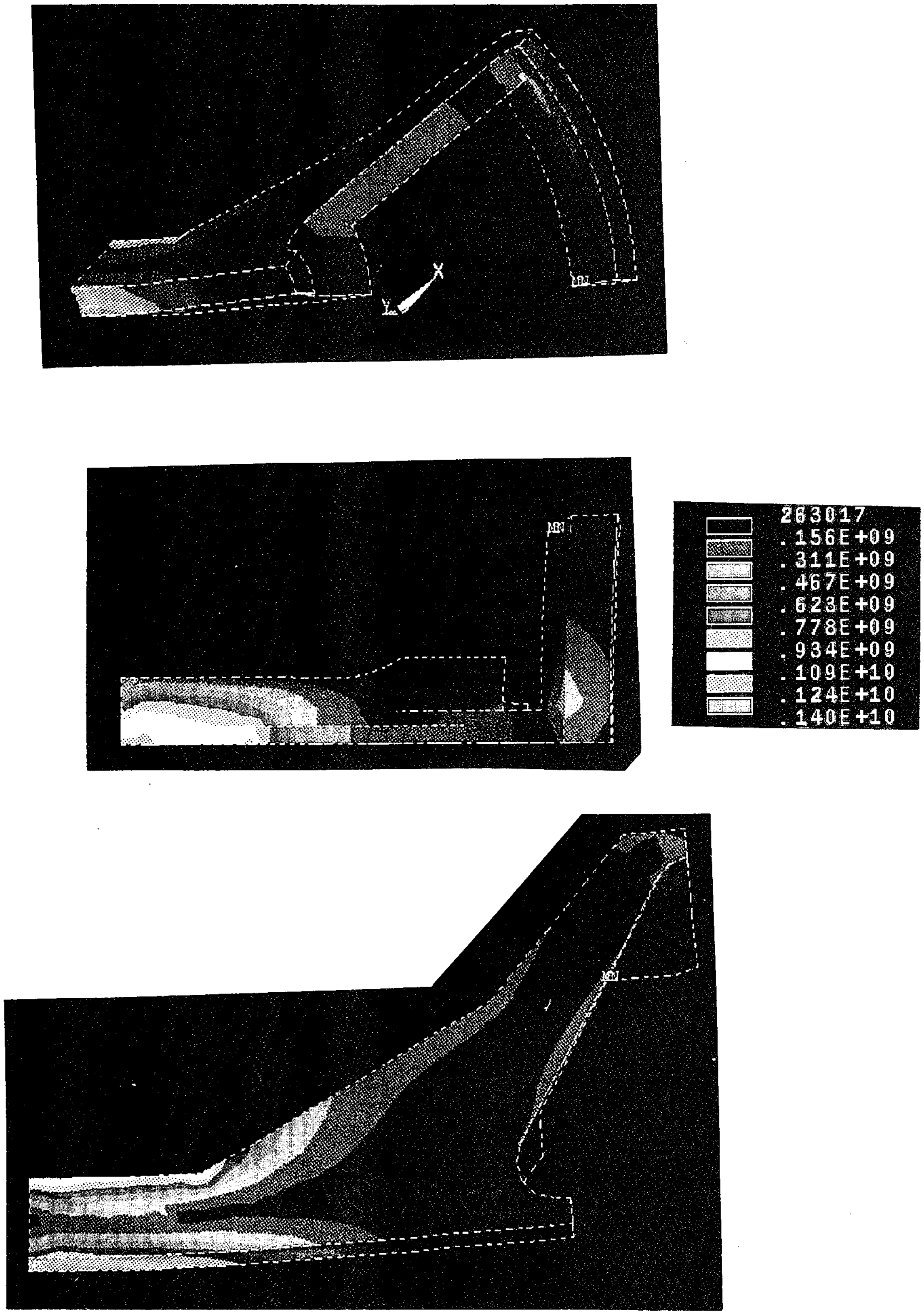

Figure 12. Case 9 stress plot - small spline addition.

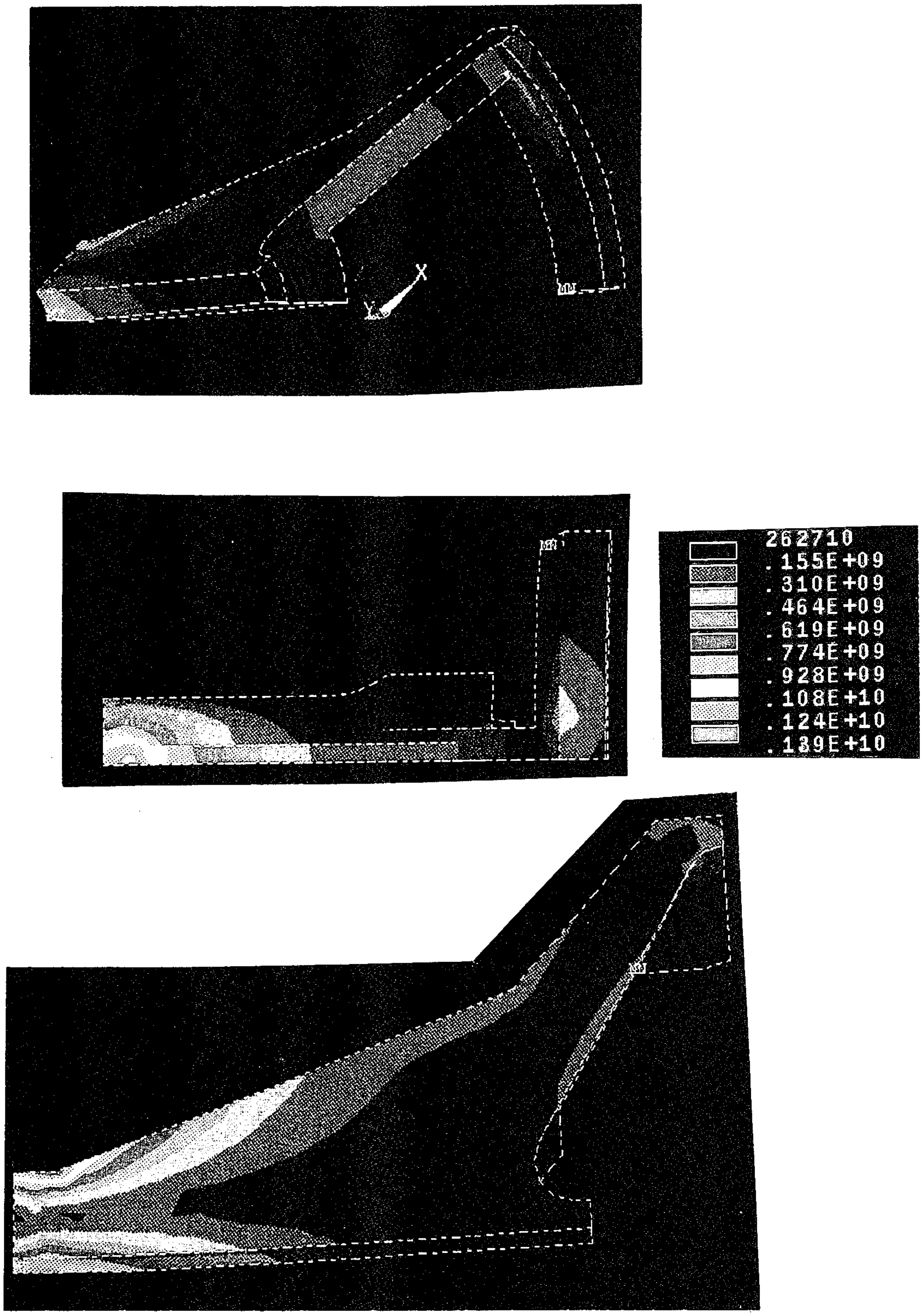

Figure 13. Case 10 stress plot - large spline addition.

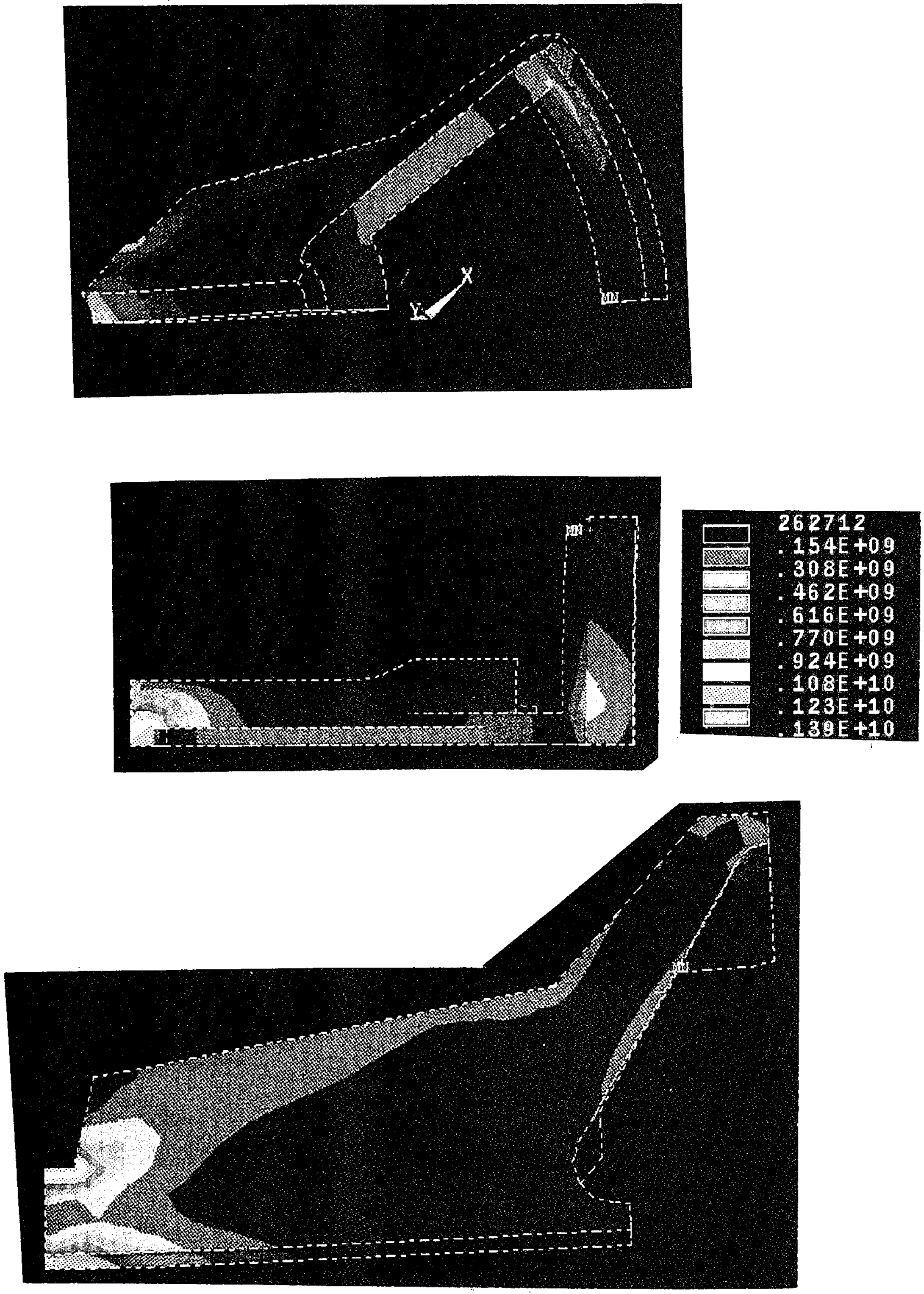

Figure 14. Case 11 stress plot - quad spline addition.

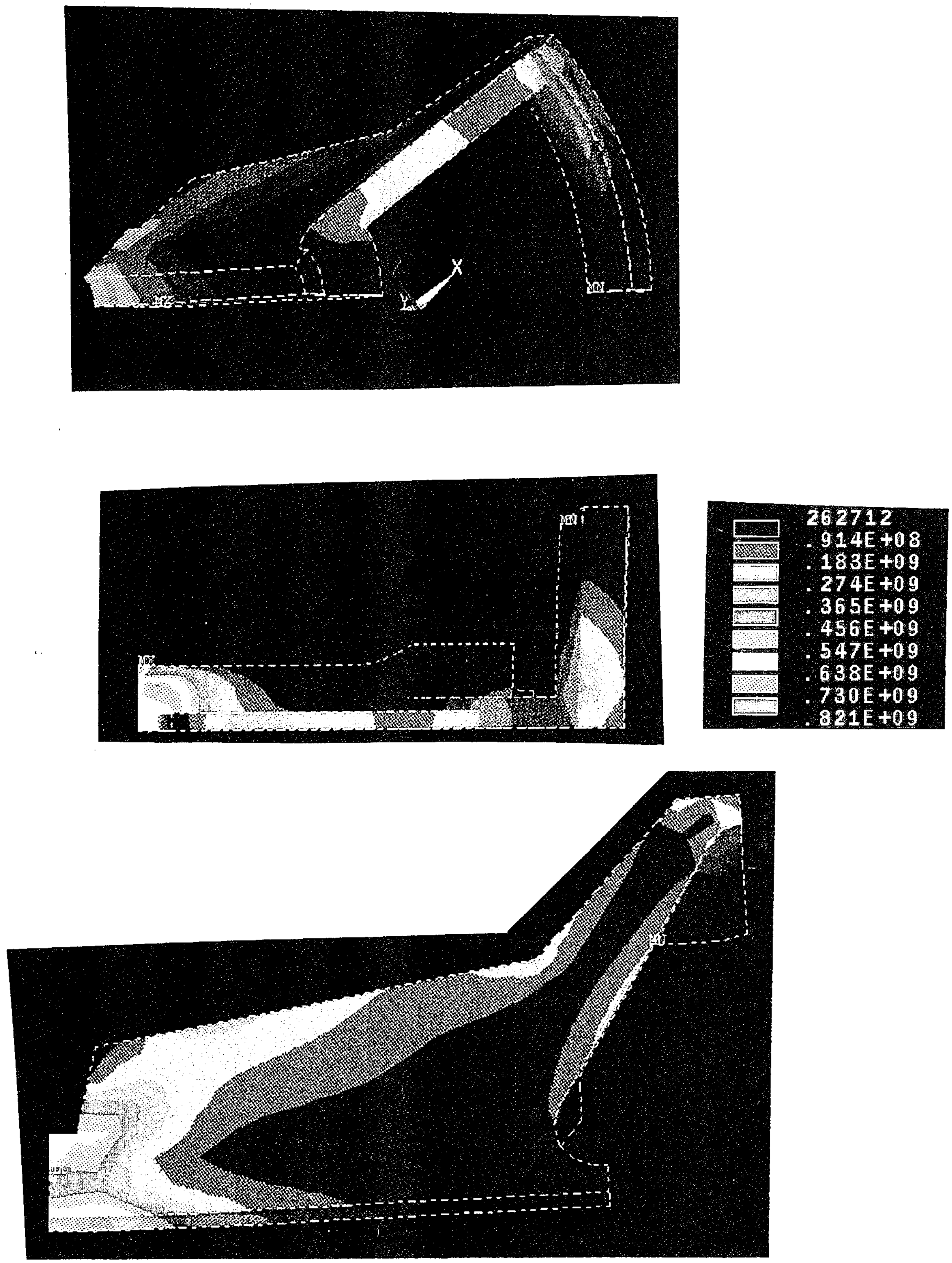

Figure 15. Case 12 stress plot - quad spline addition, elastic-plastic analysis.

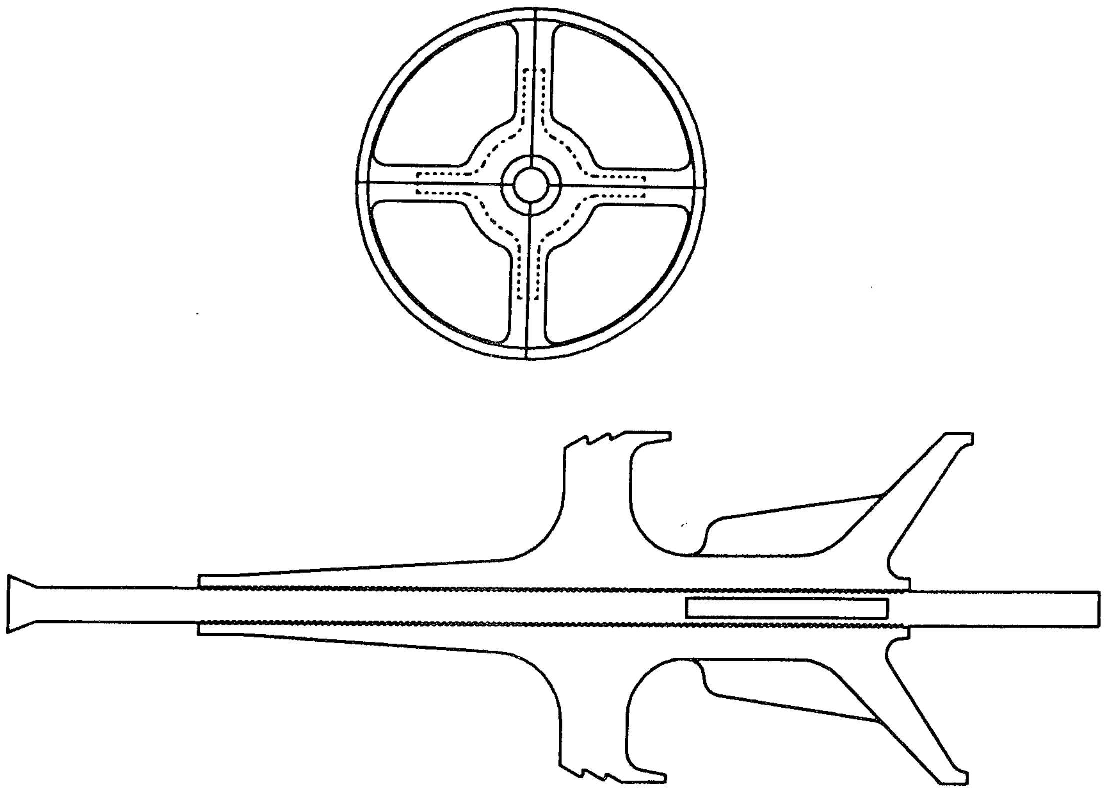

Figure 16. Final modified BFUS sabot design configuration.

This work is intended to forewarn future KE designers of the importance of performing a more detailed analysis for large-caliber, hypervelocity projectiles. The use of a window in the front borerider is presented as a means of relieving the large aerodynamic force loading on the front bell. Incorporation of splines and the thickening of the borerider support serve to reduce the bending stress present in the sabot. This investigation resulted in a structurally sound design, capable of achieving 2.4 km/s, and did not look to optimize the final geometry of the splines or borerider windows.

Four projectiles have been fabricated in the configuration shown in Figure 16. It is intended to test fire these projectiles from a double-travel 7-in cannon to obtain penetration data and verify the structural integrity of the modified sabot predicted by this analysis. The details of these test firings will be recorded in a future report.

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